Fly Ash
For
Cement Concrete

Resource For High Strength and Durability of Structures at Lower Cost

Ash Utilization Division

NTPC Limited

A-11, NFL Premises
Sector–24, Noida–201301

OUR VISION

"A world class integrated power major, powering India's growth, with increasing global presence"

OUR CORE VALUES

- Business Ethics
- Customer Focus
- Organizational & Professional Pride
- Mutual respect and Trust
- Innovation & Speed
- Total Quality for Excellence

एनटीपीसी
NTPC

टी. शंकरलिंगम
अध्यक्ष एंव प्रबन्ध निदेशक

T. SANKARALINGAM
Chairman & Managing Director

एनटीपीसी लिमिटेड
(भारत सरकार का उद्यम)

NTPC Limited
(A Govt. of India Enterprise)
(Formerly National Thermal Power Corporation Ltd.)

केन्द्रीय कार्यालय/Corporate Centre

MESSAGE

I am happy to know that Ash Utilization Division is publishing a book named "Fly Ash for Cement Concrete". Among several informative and useful insights contained in the book is the fact that mixing of ash gives higher strength and durability to concrete.

NTPC has been imparting thrust to ash utilization strategies, preparedness and implementation. The Company has developed necessary infrastructure facilities in all its coal based stations to make good quality ash available to users. Technology demonstration and awareness programmes are also being carried out. There is greater awareness of ash usage among the industrial users as well as the end users.

I am glad that ash utilization by NTPC during the year 2006-07 was 53% against MoU target of 42%. Off take by cement manufacturers for production of fly ash based PPC has been on the rise. During 2006-07, issue of fly ash to cement industry increased by 23%. In this context, this book published by NTPC Ash Utilization team will be very useful for the various user segments including builders, contractors, engineers, architects, students and other potential users.

I appreciate all the members of NTPC team who have contributed in promoting effective ash utilization and also in the compilation of this book.

(T.SANKARALINGAM)

एनटीपीसी
NTPC

चंदन रॉय
निदेशक (प्रचालन)

CHANDAN ROY
Director (Operations)

एनटीपीसी लिमिटेड
(भारत सरकार का उद्यम)

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MESSAGE

Coal-based thermal power stations account for as much as 60% of installed power generating capacity in India. The same trend is expected to continue in foreseeable future, considering availability of vast reserve of coal in India. The high percentage of fly ash content in the Indian coal has resulted in huge production of fly ash at these coal-based stations. But at the same time quality of fly ash produced is superior because of low sulphur and unburnt carbon content.

In last four decades, cement concrete technologies have shown evolutional changes and apart from the strength consideration, durability and economy have become important factors for deciding the concrete quality. The concept of higher cement content means greater strength and thus durability has not proved in true sense for the structures exposed to different climatic conditions. To make cement concrete strong and durable at lower cost, use of supplementary cementitious material i.e. fly ash started in practice and is now a proven technology World over. Thus, today cement concrete has 4 essential ingredients-cement, aggregates (coarse & fine), water and fly ash in place of traditionally 3 ingredients cement, aggregates and water. In India, though various Indian Standards published by Bureau of Indian Standard (BIS) specifies use of fly ash as part replacement of cement in concrete, in actual practice it is in nascent stage.

In the area of road construction, Indian Road Congress has also released standards for use of fly ash in Roller Compacted Concrete (RCC) roads. However there is a need to publish relevant standards for use of fly ash in RCC dams.

To create awareness among engineers, contractors, builders, architects and public at large, our Ash Utilization Division at Corporate Centre had published a variety of booklets, brochures/pamphlets etc. The details given in these publications regarding various areas of ash utilization have been appreciated very widely. The ash Utilization Division has now brought out a new book on "Fly Ash for Concrete". This new publication is expected to encourage many more engineers, builders, contractors etc to switch over to use of fly ash as an essential ingredient for production of strong and durable concrete at comparatively lower cost.

We appreciate the efforts put in by all concerned in bringing out this new book and wish all success in future in the area of ash utilization.

3RD May, 2007

(Chandan Roy)

एनटीपीसी भवन, स्कोप काम्पलैक्स, 7, इन्स्टीट्यूशनल एरिया, लोधी रोड़, नई दिल्ली-110 003, टेल/Tel. : 91-11-24360232, 24360251, फैक्स/Fax : 91-11-24363478
NTPC Bhawan, SCOPE Complex, 7, Institutional Area, Lodi Road, New Delhi-110003 Email : chandan@ntpc.co.in वेबसाइट/Website : www.ntpc.co.in

एनटीपीसी लिमिटेड
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एस.एन. पाण्डे
कार्यकारी निदेशक (पर्या., रा.उ. एवं वनरोपण)

S. N. PANDEY
Executive Director (Envt., Ash Utin. & Affor.)

MESSAGE

In India, coal will continue to remain a major source of fuel for power generation. At present, about 60% power is produced by using coal as fuel, which results in the production of about 112 million tonnes of ash per annum. Considering the tremendous growth required in the power sector for the development of Indian economy, it is expected that ash generation will reach 175 million tonne per annum by 2012 and 225 million tonne by 2017.

Ash is good resource material for utilization in various areas such as manufacture of cement, cement concrete, embankment construction, low lying area filling etc. In India, during mid seventies and early eighties, engineers / scientists responsible for making standards/ codes had understood the useful properties of the ash and necessary provision were made in various Bureau of Indian Standards (BIS) such as IS: 456-1976- Code of Practice for Plain and Reinforced Concrete, IS: 1489 (part-1)-1976 - Specification for Portland Pozzolana Cement, IS: 2250 -1981 - Code of practice for preparation of masonry mortar etc. However, fly ash utilization could not make an impact mainly because adequate arrangement for collection of fly ash at thermal power stations was not available. The quality of fly ash was not good due to high-unburnt carbon content and less fineness, and awareness was negligible.

In the eighties, era of super thermal power stations came up. Because of improved efficiency of boilers and coal mills– quality of fly ash produced in these power stations was good. NTPC has accepted the challenge for fly ash utilization and made necessary arrangements at its power stations to ensure availability of good quality fly ash. Mass awareness campaigns were carried out through brochures / pamphlets, seminars/ workshops and also by print media. These activities have shown results and our ash utilization today has crossed the 50% level.

Fly ash in cement concrete is one of the areas where huge potential exists for large-scale value added fly ash utilization on sustainable basis. It is a matter of great pleasure for me that our Ash Utilization Division has published a new book "Fly Ash for Concrete" which will surly encourage many engineers and builders to use fly ash as value added material in cement concrete.

I appreciate the efforts and wish all success to the team of our Ash Utilization Division.

SNPandey

(S. N. Pandey)

प्रथम तल, 'एफ' विंग, एन.एफ.एल. भवन, प्लाट नं. ए–11, सैक्टर–24, नोएडा-201 301, (उ० प्र०)
1st Floor, F Wing, NFL Building, Sector-24, Noida-201 301 (U.P.)
Ph. : 0120-2412746 (O), 0120-2490689 (R), FAX : 0120-2411434, E-mail : snpandey@ntpc.co.in
Regd. Office : NTPC Bhawan, Scope Complex, 7, Institutional Area, Lodhi Road, New Delhi-110 003
पंजीकृत कार्यालय : एन टी पी सी भवन, स्कोप काम्पलैक्स, 7, इन्स्टीट्यूशनल एरिया, लोधी रोड, नई दिल्ली–110003

एनटीपीसी लिमिटेड
(भारत सरकार का उद्यम)
NTPC Limited
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केन्द्रीय कार्यालय/Corporate Centre

PREFACE

NTPC- the largest power utility of India, presently, having 20% of country's installed capacity is meeting more than 28% of its power requirement. During 2006-07 about 39 million tonne of ash was produced in NTPC out which about 20.8 million tonne was gainfully utilized in various application areas such as issue to industries for manufacture of cement, bricks, construction of road embankments, mine filling, development of low lying areas etc. NTPC have ambitious plan of becoming a 51,000 MW plus Company by 2012 and 75,000 MW plus Company by 2017. The ash production is expected to be about 72 million tonne by 2012 and about 100 million tonne by 2017. NTPC is determined to play a leading role in achieving the ash utilization targets set by Ministry of Environment and Forests and help the country to achieve its National Goals.

Though, fly ash utilization in country has picked up and reached to 51 million tonnes from a meager quantity of 1 million tonne during 1994-95. Still there are certain potential areas which need special attention for full utilization of ash. Use of fly ash in Cement concrete is one such area. Fly ash use in the concrete improves many of its properties. Its use reduces heat of hydration, permeability and alkali aggregate reaction, improves workability, increased resistance to sulphate attack and corrosion thus making concrete mass more strong and durable. Besides these advantages, its use also reduces requirement of cement for same strength and thus reduces cost of concrete. World over, in many of the developed countries, fly ash is used as one of the essential ingredient of durable concrete.

In India, utilization of fly ash in cement concrete is limited mainly due to lack of required information to actual users like State / Central Govt. construction departments, builders, developers etc. An effort to present information regarding fly ash as a resource material for strong and durable concrete is attempted through this book. We do hope that this book will be useful to prospective users of fly ash, builder, developers and construction agencies. With the increased awareness in this area fly ash will be used as an essential ingredient of the concrete. This will help to increase fly ash utilization in such value added and environment friendly activities.

(A. K. Mathur)
Addl. General Manager
Ash Utilization

NTPC 1st Floor, A-11 NFL Premises, Sector-24, Noida
Tel. : 0120-2412745, Fax : 0120-2411962, Email : akmathur@ntpc.co.in

CONTENT

1.0 Introduction

Electricity is the key for development of any country. Coal is a major source of fuel for production of electricity in many countries in the world. In the process of electricity generation large quantity of fly ash get produced and becomes available as a by-product of coal-based power stations. It is a fine powder resulting from the combustion of powdered coal - transported by the flue gases of the boiler and collected in the Electrostatic Precipitators (ESP).

Conversion of waste into a resource material is an age-old practice of civilization. The fly ash became available in coal based thermal power station in the year 1930 in USA. For its gainful utilization, scientist started research activities and in the year 1937, R.E. Davis and his associates at university of California published research details on use of fly ash in cement concrete. This research had laid foundation for its specification, testing & usages.

1.1 Ash Production and its availability

Any country's economic & industrial growth depends on the availability of power. In India also, coal is a major source of fuel for power generation. About 60% power is produced using coal as fuel. Indian coal is having low calorific value (3000-3500 K cal.) & very high ash content (30-45%) resulting in huge quantity of ash is generated in the coal based thermal power stations. During 2005-06 about 112 million tonne of ash has been generated in 125 such power stations. With the present growth in power sector, it is expected that ash generation will reach to 175 million tonne per annum by 2012.

Any coal based thermal power station may have the following four kinds of ash:

Fly Ash: This kind of ash is extracted from flue gases through Electrostatic Precipitator in dry form. This ash is fine material & possesses good pozzolanic property.

Bottom Ash: This kind of ash is collected in the bottom of boiler furnace. It is comparatively coarse material and contains higher unburnt carbon. It possesses zero or little pozzolanic property.

Fly ash is loaded in closed tanker

Pond Ash: When fly ash and bottom ash or both mixed together in any proportion with the large quantity of water to make it in slurry form and deposited in ponds wherein water gets drained away. The deposited ash is called as pond ash.

Mound Ash: Fly ash and bottom ash or both mixed in any proportion and deposited in dry form in the shape of a mound is termed as mound ash.

As per the Bureau of Indian Standard IS: 3812 (Part-1) all these types of ash is termed as Pulverized Fuel Ash **(PFA).**

Fly ash produced in modern power stations of India is of good quality as it contains low sulphur & very low unburnt carbon i.e. less loss on ignition. In order to make fly ash available for various applications, most of the new thermal power stations have set up dry fly ash evacuation & storage system. In this system fly ash from Electrostatic Precipitators (ESP) is evacuated through pneumatic system and stored in silos. From silos, it can be loaded in open truck/ closed tankers or can be bagged through suitable bagging machine. In the ESP, there are 6 to 8 fields (rows) depending on the design of ESP. The field at the boiler end is called as first field & counted subsequently 2^{nd}, 3^{rd} onwards. The field at chimney end is called as last field. The coarse particles of fly ash are collected in first fields of ESP. The fineness of fly ash particles increases in subsequent fields of ESP.

1.2 Various usage of ash

Pulverized Fuel Ash is versatile resource material and can be utilized in variety of application. The pozzolanic property of fly ash makes it a resource for making cement and other ash based products. The Geo-technical properties of bottom ash, pond ash & coarse fly ash allow it to use in construction of embankments, structural fills, reinforced fills low lying area development etc. The physico chemical properties of pond ash is similar to soil and it contains P, K, Ca, Mg, Cu, Zn, Mo, and Fe, etc. which are essential nutrients for plant growth. These properties enable it to be used as a soil amender & source of micronutrients in Agriculture/ Soil Amendment.

The major utilization areas of PFA are as under: -

(1) Manufacture of Portland Pozzolana Cement & Performance improver in Ordinary Portland Cement (OPC).

(2) Part replacement of OPC in cement concrete.

(3) High volume fly ash concrete.

(4) Roller Compacted Concrete used for dam & pavement construction.

Use of ash in road embankment

(5) Manufacture of ash bricks and other building products.

(6) Construction of road embankments, structural fills, low lying area development.

(7) As a soil amender in agriculture and wasteland development.

1.3 Cenospheres

Cenospheres are lightweight, inert, hollow spheres, filled with air / gases having light grey or off white in colour and comprises largely of silica and alumina. By virtue of hollowness inside, these spherical particles imparts properties like low thermal conductivity, high electrical insulation and good sound proof characteristics. The shell is of aluminium silicate material, which provides hardness, resistance to wear and chemical inertness to particles. Because of these excellent engineering properties, cenospheres are high value material and are used as mineral fillers in plastic, polymers, rubber, paints, refractory, automotive composites, aerospace coatings and composites, propeller blades, oil well cement etc.

2.0 Cement Concrete

Cement concrete - most widely used construction material in the world over, commonly consists of cement, aggregates (fine and coarse) and water. It is the material, which is used more than any other man made material on the earth for construction works. In the concrete, cement chemically reacts with water and produces binding gel that binds other component together and creates stone type of material. The reaction process is called 'hydration' in which water is absorbed by the

cement. In this process apart from the binding gel, some amount of lime [Ca $(OH)_2$] is also liberated. The coarse and fine aggregates act as filler in the mass.

The main factors which determine the strength of concrete is amount of cement used and the ratio of water to cement in the concrete mix. However, there are some factors which limits the quantity of cement and ratio of water / cement to be used in the concrete. Hydration process of cement is exothermic and large amount of heat is liberated. Higher will be the cement content greater will be the heat liberation leading in distress to concrete.

Water is the principal constituent of the concrete mix. Once the concrete is hardened, the entrapped water in the mass is used by cement mineralogy for hydration and some water is evaporated, thus leaving pores in the matrix. Some part of these pores is filled with hydrated products of cement paste. It has been observed that higher the ratio of water / cement, higher is the porosity resulting in increased permeability.

Use of Portland cement in concrete started about 180 years ago. The concept of high strength mean higher durability developed with low-grade cement inculcated confidence and Portland cement became unique construction material of the world.

After the World war II, the need of high-speed construction necessitated the development of high-grade cement providing early high strength. The high-grade cements have been developed by changing the ratio of mineralogical constituents of the cement particularly by increasing the ratio of Tricalcium Silicate (C_3S) to Dicalcium Silicate (C_2S) and increasing the fineness of the cement. Actually, these changes have resulted in high early strength rather than high strength cement. It has been found out that buildings constructed using high grade cement during 1940-50 have ceded premature distress within 10-20 years. When the detailed analysis was carried out, it was revealed that :

1. As the hydration of cement takes place progressively, lime is also liberated gradually. A small quantity of this liberated lime is used to maintain pH of the concrete and the major portion remains unused/ surplus and makes concrete porous.

2. The high-grade cement which has high C_3S, releases higher amount of surplus lime resulting in higher porosity in the concrete mass.

3. Further, higher heat of hydration, higher water content and high porosity increases the susceptibility of concrete mass when it is exposed to a range of external and internal aggressive environment. This disturbs the soundness of the concrete and result in reduced durability.

To mitigate the above problem subsequent research work was carried out which established that use of fly ash or Pozzolana helps to solve all problems related to durability of concrete mass.

3.0 How fly ash works with Cement in Concrete?

Ordinary Portland Cement (OPC) is a product of four principal mineralogical phases. These phases are Tricalcium Silicate- C_3S ($3CaO.SiO_2$), Dicalcium Silicate - C_2S ($2CaO.SiO_2$), Tricalcium Aluminate- C_3A ($3CaO.Al_2O_3$) and Tetracalcium alumino-ferrite - C_4AF($4CaO.\ Al_2O_3.\ Fe_2O_3$). The setting and hardening of the OPC takes place as a result of reaction between these principal compounds and water. The reaction between these compounds and water are shown as under:

$2C_3S$	$+ 6H$ $\longrightarrow$	$C_3S_2H_3$	$+ 3CH$
tricalcium silicate	water	C-S-H gel	Calcium hydroxide
$2C_2S$	$+4H$ $\longrightarrow$	$C_3S_2H_3$	$+CH$
dicalcium silicate	+ water	C-S-H gel	Calcium hydroxide

The hydration products from C_3S and C_2S are similar but quantity of calcium hydroxide (lime) released is higher in C_3S as compared to C_2S .

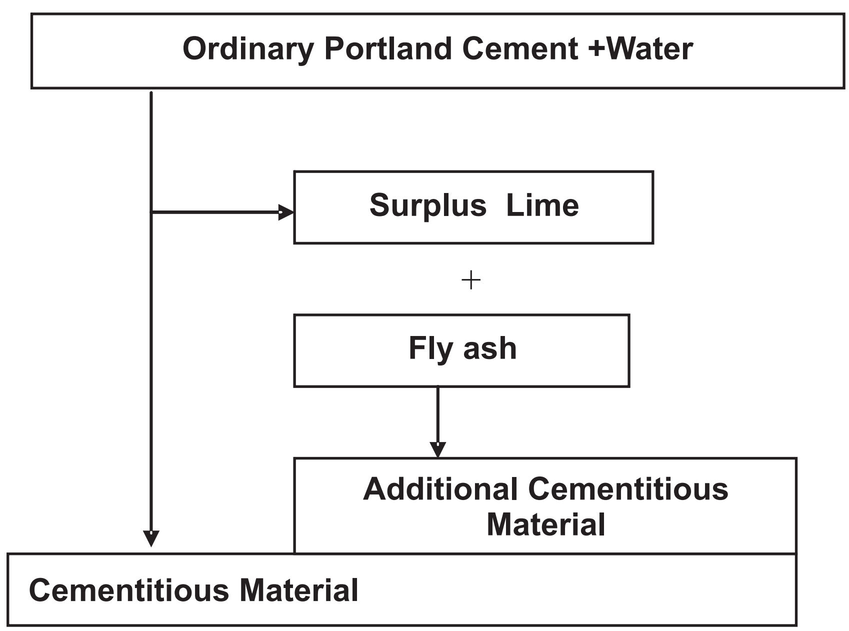
The reaction of C_3A with water takes place in presence of sulphate ions supplied by dissolution of gypsum present in OPC. This reaction is very fast and is shown as under:

C_3A	$+\ 3(CSH_2)$	$+\ 26H$	$\longrightarrow$	$C_3\,A(CS)_3\,H_{32}$
tricalcium alluminate	+ gypsum	+ water	$\longrightarrow$	ettringite
$C_3A + CSH_2$	$+ 10H$		$\longrightarrow$	C_3ACSH_{12}
				monosulphoaluminate hydrate

Tetracalcium alumino-ferrite forms hydration product similar to those of C_3A, with iron substituting partially for alumina in the crystal structures of ettringite and monosulpho-aluminate hydrate.

Above reactions indicate that during the hydration process of cement, lime is released out and remains as surplus in the hydrated cement. This leached out surplus lime renders deleterious effect to concrete such as make the concrete porous, give chance to the development of micro- cracks, weakening the bond with aggregates and thus affect the durability of concrete.

If fly ash is available in the mix, this surplus lime becomes the source for pozzolanic reaction with fly ash and forms additional C-S-H gel having similar binding properties in the concrete as those produced by hydration of cement paste. The reaction of fly ash with surplus lime continues as long as lime is present in the pores of liquid cement paste. The process can also be understood as follows:



4.0 How fly ash helps in concrete?

4.1 Reduced Heat of Hydration

In concrete mix, when water and cement come in contact, a chemical reaction initiates that produces binding material and consolidates the concrete mass.

The process is exothermic and heat is released which increases the temperature of the mass. When fly ash is present in the concrete mass, it plays dual role for the strength development. Fly ash reacts with released lime and produces binder as explained above and render additional strength to the concrete mass. The un-reactive portion of fly ash act as micro aggregates and fills up the matrix to render packing effect and results in increased strength.

The large temperature rise of concrete mass exerts temperature stresses and can lead micro crackes. When fly ash is used as part of cementitious material, quantum of heat liberated is low and staggers through pozzolanic reactions and thus reduces micro-cracking and improves soundness of concrete mass.

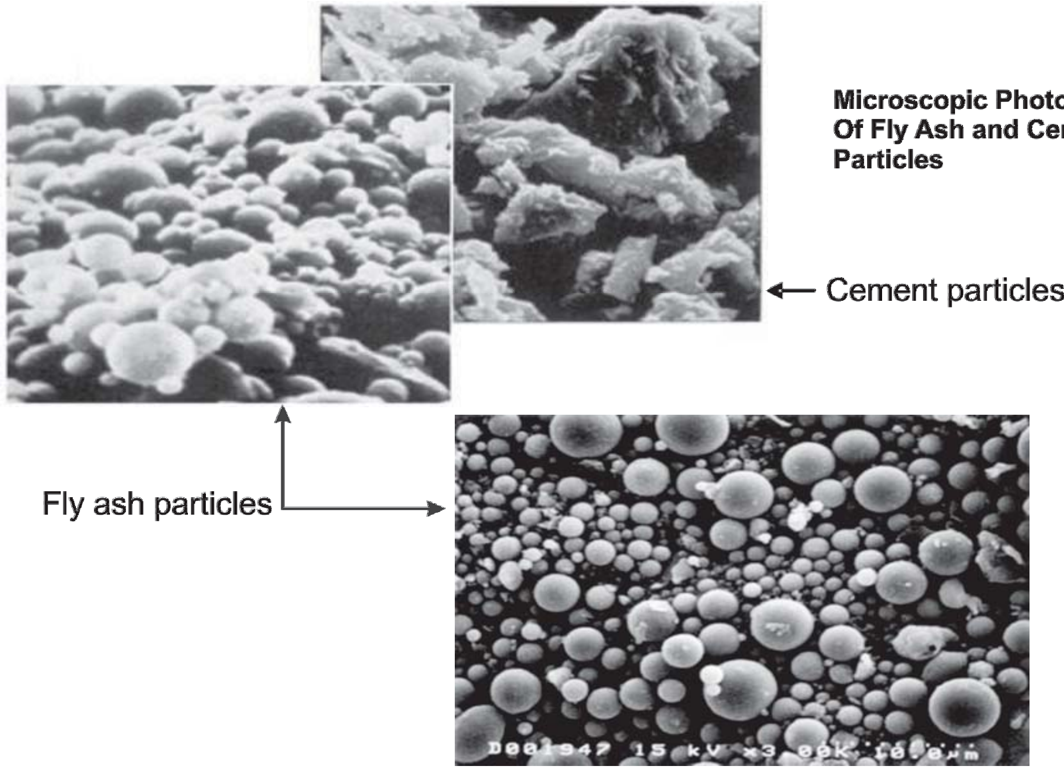
4.2 Workability of Concrete

Fly ash particles are generally spherical in shape and reduces the water requirement for a given slump. The spherical shape helps to reduce friction between aggregates and between concrete and pump line and thus increases workability and improve pumpability of concrete. Fly ash use in concrete increases fines volume and decreases water content and thus reduces bleeding of concrete.

4.3 Permeability and corrosion protection

Water is essential constituent of concrete preparation. When concrete is hardened, part of the entrapped water in the concrete mass is consumed by cement mineralogy for hydration. Some part of entrapped water evaporates, thus leaving porous channel to the extent of volume occupied by the water. Some part of this porous volume is filled by the hydrated products of the cement paste. The remaining part of the voids consists capillary voids and give way for ingress of water. Similarly, the liberated lime by hydration of cement is water-soluble and is leached out from hardened concrete mass, leaving capillary voids for the ingress of water. Higher the water cement ratio, higher will be the porosity and thus higher will be the permeability. The permeability makes the ingress of moisture and air easy and is the cause for corrosion of reinforcement. Higher permeability facilitate ingress of chloride ions into concrete and is the main cause for initiation of chloride induced corrosion.

Additional cementitious material results from reaction between liberated surplus lime and fly ash, blocks these capillary voids and also reduces the risk of leaching of surplus free lime and thereby reduces permeability of concrete.



Microscopic Photographs Of Fly Ash and Cement Particles

4.4 Effect of fly ash on Carbonation of Concrete

Carbonation phenomenon in concrete occurs when calcium hydroxides (lime) of the hydrated Portland Cement react with carbon dioxide from atmospheres in the presence of moisture and form calcium carbonate. To a small extent, calcium carbonate is also formed when calcium silicate and aluminates of the hydrated Portland cement react with carbon dioxide from atmosphere. Carbonation process in concrete results in two deleterious effects (i) shrinkage may occur (ii) concrete immediately adjacent to steel reinforcement may reduce its resistance to corrosion. The rate of carbonation depends on permeability of concrete, quantity of surplus lime and environmental conditions such as moisture and temperature. When fly ash is available in concrete; it reduces availability of surplus lime by way of pozzolanic reaction, reduces permeability and as a result improves resistance of concrete against carbonation phenomenon.

4.5 Sulphate Attack

Sulphate attacks in concrete occur due to reaction between sulphate from external origins or from atmosphere with surplus lime leads to formation of etrringite, which

causes expansion and results in volume destabilization of the concrete. Increase in sulphate resistance of fly ash concrete is due to continuous reaction between fly ash and leached out lime, which continue to form additional C-S-H gel. This C-S-H gel fills in capillary pores in the cement paste, reducing permeability and ingress of sulphate ions.

4.6 Corrosion of steel

Corrosion of steel takes place mainly because of two types of attack. One is due to carbonation attack and other is due to chloride attack. In the carbonation attack, due to carbonation of free lime, alkaline environment in the concrete comes down which disturbs the passive iron oxide film on the reinforcement. When the concrete is permeable, the ingress of moisture and oxygen infuse to the surface of steel initiates the electrochemical process and as a result-rust is formed. The transformation of steel to rust increases its volume thus resulting in the concrete expansion, cracking and distress to the structure.

In the chloride attack, Chloride ion becomes available in the concrete either through the dissociation of chlorides-associated mineralogical hydration or infusion of chloride ion. The sulphate attack in the concrete decomposes the chloride mineralogy thereby releasing chloride ion. In the presence of large amount of chloride, the concrete exhibits the tendency to hold moisture. In the presence of moisture and oxygen, the resistivity of the concrete weakens and becomes more permeable thereby inducing further distress. The use of fly ash reduces availability of free limes and permeability thus result in corrosion prevention.

4.7 Reduced alkali- aggregate reaction

Certain types of aggregates react with available alkalis and cause expansion and damage to concrete. These aggregates are termed as reactive aggregates. It has been established that use of adequate quantity of fly ash in concrete reduces the amount of alkali aggregate reaction and reduces/ eliminates harmful expansion of concrete. The reaction between the siliceous glass in fly ash and the alkali hydroxide of Portland cement paste consumes alkalis thereby reduces their availability for expansive reaction with reactive silica aggregates.

In a nutshell, it can be summarized that permeability and surplus lime liberated during the hydration of Portland cement are the root causes for deleterious effect on the concrete. Impermeability is the foremost defensive

mechanism for making concrete more durable and is best achieved by using fly ash as above.

Salient advantage of using fly ash in cement concrete
• Reduction in heat of hydration and thus reduction of thermal cracks and improves soundness of concrete mass.
• Improved workability / pumpabilty of concrete
• Converting released lime from hydration of OPC into additional binding material – contributing additional strength to concrete mass.
• Pore refinement and grain refinement due to reaction between fly ash and liberated lime improves impermeability.
• Improved impermeability of concrete mass increases resistance against ingress of moisture and harmful gases result in increased durability.
• Reduced requirement of cement for same strength thus reduced cost of concrete.

4.8 Environmental benefits of fly ash use in concrete

Use of fly ash in concrete imparts several environmental benefits and thus it is eco-friendly. It saves the cement requirement for the same strength thus saving of raw materials such as limestone, coal etc required for manufacture of cement.

Manufacture of cement is high-energy intensive industry. In the manufacturing of one tonne of cement, about 1 tonne of CO_2 is emitted and goes to atmosphere. Less requirement of cement means less emission of CO_2 result in reduction in green house gas emission.

View of tunnel of Delhi Metro Rail Corporation where fly ash has been used

Due to low calorific value and high ash content in Indian Coal, thermal power plants in India, are producing huge quantity of fly ash. This huge quantity is being stored / disposed off in ash pond areas. The ash ponds acquire large

areas of agricultural land. Use of fly ash reduces area requirement for pond, thus saving of good agricultural land.

5.0 Chemistry of Fly ash

Fly ash is complex material having wide range of chemical, physical and mineralogical composition. The chemistry of fly ash depends on the type of coal burnt in boiler furnace, temperature of furnace, degree of pulverization of coal, efficiency of ESP etc.

Fly ash from NTPC Dadri has been used in building constructed at Gurgaon, Haryana

5.1 Chemical Composition

The major constituents of most of the fly ashes are Silica (SiO_2), alumina ((Al_2O_3), ferric oxide (Fe_2O_3) and calcium oxide (CaO). The other minor constituent of the fly ash are MgO, Na_2O, K_2O, SO_3, MnO, TiO_2 and unburnt carbon. There is wide range of variation in the principal constituents - Silica (25-60%), Alumina (10-30%) and ferric oxide (5-25%). When the sum of these three principal constituents is 70% or more and reactive calcium oxide is less than 10% - technically the fly ash is considered as **siliceous fly ash** or class F fly ash. Such type of fly ash is produced by burning of anthracite or bituminous coal and possess pozzolanic properties. If the sum of these three constituent is equal or more than 50% and reactive calcium oxide is not less than 10%, fly ash will be considered as **Calcareous fly ash** also called as class C fly ash. This type of fly ash is commonly produced by burning of lignite or sub-bituminous coal and possess both pozzolanic and hydraulic properties.

Siliceous fly ash characteristically contains a large part of silicate glass of high silica content and crystalline phases of low reactivity mullite, magnetite and quartz. The active constituents of class F fly ash is siliceous or alumino-silicate glass. **In calcareous or class C fly ash,** the active constituents are calcium alumino-silicate glass, free lime (CaO), anhydrate ($CaSO_4$), tricalcium aluminate and rarely, calcium silicate. The glassy materials of fly ash are reactive with the calcium and alkali hydroxides released from cement fly ash system and forms cementitious gel, which provide additional strength.

5.2 Physical Properties:

The fly ash particles are generally glassy, solid or hollow and spherical in shape. The hollow spherical particles are called as cenospheres. The fineness of individual fly ash particle rage from 1 micron to 1 mm size. The fineness of fly ash particles has a significant influence on its performance in cement concrete. The fineness of particles is measured by measuring specific surface area of fly ash by Blaine's specific area technique. Greater the surface area more will be the fineness of fly ash. The other method used for measuring fineness of fly ash is dry and wet sieving.

The specific gravity of fly ash varies over a wide range of 1.9 to 2.55.

5.3 Pozzolanic Properties of fly ash

Fly Ash is a pozzolanic material which is defined as siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value, chemically react with Calcium Hydroxide (lime) in presence of water at ordinary temperature and form soluble compound comprises cementitious property similar to cement.

The pozzolana term came from Roman. About 2,000 years ago, Roman used volcanic ash along with lime and sand to produce mortars, which possesses superior strength characteristics & resistances to corrosive water. The best variety of this volcanic ash was obtained from the locality of pozzoli and thus the volcanic ash had acquired the name of Pozzolana.

5.4 Pozzolanic Activity

Pozzolanic activity of fly ash is an indication of the lime fly ash reaction. It is mostly related to the reaction between reactive silica of the fly ash and calcium hydroxide which produce calcium silicate hydrate (C-S-H) gel which has binding properties. The alumina in the pozzolana may also react in the fly ash lime or fly ash cement system and produce calcium aluminate hydrate, ettringite, gehlenite and calcium monosulpho-aluminate hydrate. Thus the sum of reactive silica and alumina in the fly ash indicate the pozzolanic activity of the fly ash.

6.0 Quality of Fly Ash as per BIS, ASTM

6.1 Bureau of Indian Standard

To utilize fly ash as a Pozzolana in Cement concrete and Cement Mortar, Bureau of Indian Standard (BIS) has formulated IS: 3812 Part - 1 2003. In this code quality requirement for siliceous fly ash (class F fly ash) and calcareous fly ash (class C fly ash) with respect its chemical and physical composition have been specified. These requirements are given in table 1 & table 2:

Table 1

Chemical Requirements

Sl. No.	Characteristic	Requirements	
		Siliceous fly ash	**Calcareous fly ash**
i)	**Silicon dioxide** (SiO_2) + **Aluminium oxide** (Al_2O_3) + **Iron oxide** (Fe_2O_3), in percent by mass, Min..	**70**	**50**
ii)	**Silicon dioxide** in percent by mass, Min.	**35**	**25**
(iii)	**Reactive Silica** in percent by mass, Min (Optional Test)	**20**	**20**
iv)	**Magnesium Oxide** (MgO), in percent by mass, Max. .	**5.0**	**5.0**
v)	**Total sulphur as sulphur trioxide** (SO_3), in percent by mass, Max.	**3.0**	**3.0**
vi)	**Available alkalis** as Sodium oxide (Na_2O), percent by mass, Max.	**1.5**	**1.5**
vii)	**Total Chlorides** in percent by mass, Max	**0.05**	**0.05**
viii)	**Loss on Ignition**, in percent by mass, Max.	**5.0**	**5.0**

Table 2
Physical Requirements

Sl. No	Characteristics	Requirements for Siliceous fly ash and Calcareous fly ash
i)	**Fineness-** Specific surface in m^2/kg by Blaine's permeability method, Min.	320
ii)	**Particles** retained on 45 micron IS sieve (wet sieving) in percent, Max. (Optional Test)	34
iii)	**Lime reactivity** – Average compressive strength in N/mm^2, Min.	4.5
iv)	**Compressive strength** at 28 days in N/mm^2, Min.	Not less than 80 percent of the strength of corresponding plain cement mortar cubes
v)	**Soundness by autoclave test -** Expansion of specimen in percent, Max.	0.8

6.2 ASTM International for Fly ash

ASTM International C-618-03 specifies the chemical composition and physical requirements for fly ash to be used as a mineral admixture in concrete. The standard requirements are given in table 3 and table 4:

Table 3
Chemical Requirements

Sl. No.	Characteristic	Requirements	
		Class F (Siliceous fly ash)	**Class C (Calcareous fly ash)**
i)	**Silicon dioxide** (SiO_2) + **Aluminium oxide** (Al_2O_3) + **Iron oxide** (Fe_2O_3), in percent by mass, Min..	**70**	**50**
ii)	**Sulfur trioxide (SO_3), max. Percent**	**5.0**	**5.0**
(iii)	**Moisture content, max. , percent**	**3.0**	**3.0**
(iv)	**Loss on ignition, max., percent**	**6.0**	**6.0**

Table 4
Physical Requirements

Sl. No.	Characteristics	Requirements for class F & Class C fly ash
i)	**Fineness-** amount retained when wet-sieved on 45 micron (No. 325) sieve, Max. , percent	34
ii)	**Strength Activity index**	
	• With Portland Cement, at 7 days, min. , percent of control	75^{C}
	• With Portland cement, at 28 days, min,, percent of control	75^{C}
iii)	Water requirement, max, percent of control	105
iv)	**Soundness** Autoclave expansion or contraction, Max., percent	0.8
v)	**Uniformity Requirements:** The density and fineness of individual samples shall not vary from the average established by ten preceding tests, or by all preceding tests if the number is less than ten, by more than	
	• Density, max. variation from average, percent.	5
	• Percent retained on 45 micron (no. 325), max. variation, percentage points from average	5

7.0 How Fly ash can be used in Cement Concrete?

The main objective of using fly ash in most of the cement concrete applications is to get durable concrete at reduced cost, which can be achieved by adopting one the following two methods:

1. Using Fly ash based Portland Pozzolana Cement (PPC) conforming to IS:1489 Part-1 in place of Ordinary Portland Cement

2. Using fly ash as an ingredient in cement concrete.

The first method is most simple method, since PPC is factory-finished product and does not requires any additional quality check for fly ash during production of concrete. In this method the proportion of fly ash and cement is, however, fixed and limits the proportioning of fly ash in concrete mixes.

The addition of fly ash as an additional ingredients at concrete mixing stage as part replacement of OPC and fine aggregates is more flexible method. It allows for maximum utilization of the quality fly ash as an important component (cementitious and as fine aggregates) of concrete.

There are three basic approaches for selecting the quantity of fly ash in cement concrete:

(i) Partial Replacement of Ordinary Portland Cement (OPC)- **the simple replacement method**

(ii) Addition of fly ash as fine aggregates **the addition method**

(iii) Partial replacement of OPC, fine aggregate, and water- **a modified replacement method**

7.1 Simple replacement method

In this method a part of the OPC is replaced by fly ash on a one to one basis by mass of cement. In this process, the early strength of concrete is lower and higher strength is developed after 56-90 days. At early ages fly ash exhibits very little cementing value. At later ages when liberated lime resulting from hydration of cement, reacts with fly ash and contributes considerable strength to the concrete. This method of fly ash use is adopted for mass concrete works where initial strength of concrete has less importance compared to the reduction of temperature rise.

7.2 Addition Method

In this method, fly ash is added to the concrete without corresponding reduction in the quantity of OPC. This increases the effective cementitious content of the

concrete and exhibits increased strength at all ages of the concrete mass. This method is useful when there is a minimum cement content criteria due to some design consideration.

7.3 Modified replacement method

This method is useful to make strength of fly ash concrete equivalent to the strength of control mix (without fly ash concrete) at early ages i.e. between 3 and 28 days. In this method fly ash is used by replacing part of OPC by mass along with adjustment in quantity of fine aggregates and water. The concrete mixes designed by this method will have a total weight of OPC and fly ash higher than the weight of the cement used in comparable to control mix i.e. without fly ash mix. In this method the quantity of cementitious material (OPC + Fly ash) is kept higher than quantity of cement in control mix (without fly ash) to offset the reduction in early strength.

8.0 Mix Design for Fly ash based concrete

Cement Concrete is principally made with combination of cement (OPC / PPC/ Slag), aggregate and water. It may also contain other cementitious materials such as fly ash, silica fumes etc. and / or chemical admixture. Use of Fly ash along with cement helps to provide specific properties like reduced early heat of hydration, increased long term strength, increased résistance to alkali aggregate reaction and sulphate attack, reduced permeability, résistance to the intrusion of aggressive solutions and also economy. Chemical admixture are used to accelerate, retard, improve workability, reduce mixing water requirement, increase strength or alter other properties of the concrete.

8.1 Criteria for Mix Design

The selection of concrete proportions involves a balance between economy and requirements for workability and consistency, strength, durability, density and appearance for a particular application. In addition, when mass concrete is being proportioned, consideration is also given to heat of hydration.

Workability and Consistency

Workability is considered to be that property of concrete, which determines its capacity to be placed, compacted properly and finished without segregation.

Workability is affected by: the grading, particle shape, proportions of aggregate, the quantity & qualities of cement + cementitious materials, the presence of entrained air and chemical admixtures, and the consistency of the mixture. Consistency is defined as the relative mobility of the concrete mixture. It is measured in terms of slump. The higher the slump the more mobile the mixture- and it affects the ease with which the concrete will flow during placement. It is related with workability. In properly proportioned concrete, the unit water content required to produce a given slump will depend on several factors. Water requirement increases as aggregates become more angular and rough textured. It decreases as the maximum size of well- graded aggregate is increased. It also decreases with the entrainment of air. Certain water- reducing admixtures reduce mixing water requirement significantly.

Strength-

Although strength is an important characteristics of concrete, other characteristics such as durability, permeability and wear resistance are often equally or more important. Strength at the age of 28 days is generally used as a parameter for the structural design, concrete proportioning and evaluation of concrete. Strength mainly depends on water - cement or water - cementitious material ratio [w/c or w/(c+p)]. For a given set of materials and conditions, concrete strength is determined by the net quantity of water used per unit quantity of cement or total cementitious materials. The net water content excludes water absorbed by the aggregates. Difference in strength for a given water- cement (w/c) ratio or water-cementitious materials {w/(c+p)} ratio (p indicates pozzolana or supplementary cementitious materials) may result from changes in: maximum size of aggregate; grading, surface texture, shape, strength, stiffness of aggregate particles, differences in cement types and sources, air content, and the use of chemical admixtures that affect the cement hydration process or develop cementitious properties themselves.

Durability-

Concrete must be able to endure those exposures that may deprive it of its serviceability- heating & cooling, wetting & drying, freezing & thawing in cold countries, chemicals, de-icing agents etc. Resistance to some of these may be enhanced by use of special ingredients, low-alkali cement, fly ash, Ground Granulated Blast Furnace (GGBF) slag, and silica fume. The durability of concrete exposed to seawater or sulfate- bearing soils, or aggregate composed of hard

minerals and free of excessive soft particles where resistance to surface abrasion is required can also be enhanced substantially by using above special ingredients. Use of low water-cement or water cementitious materials ratio [w/c or w/(c+p)] will prolong the life of concrete by reducing the penetration of aggressive liquids.

Density-

For certain applications, concrete may be used primarily for its weight characteristics. Examples of such applications are counterweights on lift bridges, dams, weights for sinking oil pipelines under water, shielding from radiation and insulation from sound.

Heat of Hydration-

A major concern in proportioning mass concrete is the size and shape of the completed structure or portion thereof. If the temperature rise of the concrete mass is not controlled a minimum and the heat is allowed to dissipate at a reasonable rate, or if the concrete is subjected to severe temperature differential or thermal gradient, cracking is likely to occur. Thermal cracking of foundation, floor slabs, beams, columns, bridge piers and other massive structure such as dams can or may reduce the service life of a structure by promoting early deterioration and may need excessive maintenance. Utilization of fly ash provides a partial replacement of cement with material, which generates considerable less heat at early ages. The early age heat contribution of a pozzolana may conservatively be estimated to a range between 15 to 50 percent of that of an equivalent weight of concrete. The required temperature control measures can thus be suitably reduced.

8.2 Proportioning of Concrete

The selection of concrete proportions involves a balance between economy and various criteria defined in para 8.1 above. Proportioning or mix design of concrete involves a sequence of logical, straight forward steps which in effect fit the characteristics of the available materials into a mixture suitable for the work. Steps to be followed for proportioning of concrete utilizing fly ash are given below. These guidelines are based on “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)” of American Concrete Institute (ACI).

Step 1. Selection of slump for requirement of consistency

If slump is not specified, a value appropriate for the work can be selected from Table (a). The slump ranges shown apply when vibration is used to consolidate the concrete. The maximum value of slump may be increased by 25 mm if the method of consolidation adopted is other than vibration.

Table (a)

Recommended slumps in ACI 211.1-91 for various types of constructions

Type of Construction	Slumps (mm)	
	Maximum	Minimum
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and sub structure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

Step-2 Selection of maximum size of aggregates

Large nominal maximum sizes of well-graded aggregates have less voids than smaller size aggregates. This results in, concrete with the larger sized aggregates require less mortar per unit volume of concrete. Therefore, the nominal maximum size of aggregates should be the largest that is economically available and consistent with the dimensions of the structure. However, nominal maximum size of aggregates should not be more than (i) one fifth of the narrowest dimension between sides of forms.(ii) one third of the depth of slab (iii) three fourths of the minimum clear spacing between individual reinforcing bars/ bundles of bars or pretensioning strands. These limitations are sometimes can be relaxed if workability and methods of consolidation are such that the concrete can be placed without honeycombs or voids.

Step 3: Estimation of mixing water and air content

The quantity of water per unit volume of concrete required to produce a given slump is dependent on: the nominal maximum size, particle shape, grading of the

aggregates; the concrete temperature; the amount of entrained air and use of chemical admixture. Slump is not greatly affected by the quantity of cement or cementitious material. Estimates of required mixing water for concrete, with or without air entrainment recommended by ACI (American Concrete Institutes) 212.1R are given in table (b)

Table (b)
Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates

Slump (mm)	Water, kg/m³ of concrete for indicated nominal maximum sizes of aggregates							
	9.5*	12.5*	19*	25*	37.5*	50†*	75†‡	150†‡
Non –air entrained concrete								
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
Approximate amount of entrapped air in non -air entrai ned concrete, percent.	3	2.5	2	1.5	1	0.5	0.3	0.2
Air –entrained concrete								
25 to 50	181	175	168	160	150	142	122	107
75 to 100	202	193	184	175	165	157	133	119
150 to 175	216	205	197	184	174	166	154	-
Recommended average total air content, percent for level of exposure								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**††	1.0**††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**††	3.0**††
Extreme ‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**††	4.0**††

* The quantity of mixing water given for air entrained concrete are based on typical total air content requirement and as shown for “moderate exposure” in the table above. These quantities of mixing water are used in assessing cement content for trial basis at 20^0 to 25^0 C. They are maximum for reasonably well-shaped angular aggregates grading within limits of accepted specification. Rounded course aggregate will generally require 18 kg less water for non-air-entrained and 15 kg less for air-entrained concrete. The use of water reducing chemical admixture may also reduce mixing water by 5% or more. The volume of liquid admixture is included as part of total volume of mixing water.

†The slump values of concrete containing aggregate larger than 40 mm are based on slump tests made after removal of particles larger than 40 mm by wet screening.

‡These quantities of mixing water are for use in computing cement factors for trial batches when 75 mm or 150 mm nominal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregate, well graded from coarse to fine.

** For concrete containing large aggregate which will be wet screen over the 40 mm for prior to testing of air content, the % of air expected in the 40 mm minus material should be as tabulated in 40 mm column. However, initial proportioning calculations should include the air content as a % of whole.

†† When using large aggregate in low cement factor concrete, air entrainment need not to be detrimental to strength. In most cases, mixing water requirement is reduced sufficiently to improve the water cement ratio and to thus compensate for the strength reducing effect of entrained air concrete. Generally, therefore, for these large nominal maximum sizes of aggregate, air contents recommended for extreme exposure should be considered even though there may be a little or no exposure to moisture and freezing.

‡‡ These values are based on criterion that 9% air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined from this recommend practice, it may be desirable to calculate the needed air content by taking 9% or actual mortar value.

Step 4 - Selection of water cementitious materials [w /(c+p)] or water cement ratio (w/c)

The approximate values corresponding to compressive strength at 28 days under standard laboratory conditions are given in table (c), which can be used for selection of water cementitious materials [w /(c+p)] or water cement (w/c) ratio for concrete proportioning.

Table (c)
Relationship between water cementitious materials ratio and compressive strength of Cement

Compressive strength at 28 days, MPa *	*Water – Cement ratio by mass*	
	Non –air entrained concrete	Air entrained concrete
40	0.42	-
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

* Values are estimated average strength for concrete containing not more than 2% air for non-air-entrained concrete and 6% total air content for air-entrained concrete. For constant water-cement ratio, the strength of concrete is reduced as the air content is increased.

Strength is based on 152 x305 mm cylinder moist-cured for 28 days in accordance with standard norms specified in relevant ASTM code.

The relationship given in the above table is based on the nominal maximum size of about 19 to 25 mm. For given source of aggregate, strength produced at given water -cement ratio will increase as nominal maximum size of aggregates decreases.

Fly ash 15-35% by weight of total cementitious material can be used as part replacement of Ordinary Portland cement. When high early strength is required, the total weight of cementitious material (Cement + fly ash) may be kept greater than the

quantity that would be need if Portland Cement were the only cementitious material. When high early strength is not required higher percentage of fly ash can be used.

When fly ash is used in concrete, a water-to- cement + fly ash ratio by weight must be considered in place of the traditional water-cement ratio (w/c) by weight.

Step 5- Calculation of cementitious material content:

The amount of cementitious material (c + p) per unit volume of concrete can be determined by selecting the mixing water content and the water to cementitious material ratio as described in step 3 & 4. However, if minimum cementitious material requirement is specified for strength and durability criteria, in that case higher quantity of cementitious content will be used in the mix.

Step 6- Estimation of coarse aggregate content

Nominal maximum size and grading will produce concrete of satisfactory workability when a given volume of coarse aggregates, on an oven dry-rodded basis, is used per unit volume of concrete. The approximate value of dry mass of coarse aggregate required for a cubic meter of concrete can be worked out by taking value corresponding to nominal maximum size of aggregate from table (d) and multiplying by the dry- rodded unit mass of aggregates in kg.

Table (d)
Volume of Coarse Aggregate Per Unit of Volume of Concrete

Nominal Maximum size of aggregate, mm	Volume of dry- rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

Step 7 Estimation of fine aggregate content

The fine aggregate content can be worked out from the formula given below:

Wet density of concrete (kg/m^3) - weight of (cement + fly ash + water + coarse agreegates) in kg

Normally wet density of concrete is taken as 2400 kg/m^3

Step 8 Adjustments for aggregate moisture

The aggregate quantities actually to be weighted out for the concrete must allow for moisture in the aggregates. Generally, aggregates are moist and their dry weights should be increased by the percentage of water they contain (both absorbed and surface). The mixing water to be added in a batch must be reduced by an amount equal to the free moisture contributed by aggregate i.e. total moisture minus absorption.

Trial batch adjustment

The estimated mixture proportion is to be checked by trial batches prepared and tested according to standard practice for compressive strength, slump, unit weight etc. In the trial batch sufficient water should be used to produce the required slump regardless of the amount assumed in selecting the trial proportions. The trial batches should be carefully observed for proper workability, freedom from segregation and finishing properties. Appropriate adjustment should be made in the proportions for subsequent batches.

By following above-mentioned steps, designing of cement concrete mix using fly ash as a cementitious material for partly replacing cement can be carried out for desired strength and durability.

9.0 Bureau of Indian Standards stipulations for use of fly ash in concrete:

As per clause 5.2 of IS 456-2000 Plain and Reinforced cement concrete code of practice, fly ash (conforming to IS 3812 part 1) up to 35% can be used as part replacement of OPC in the concrete. As per the note of table 5 of this code of practice, addition of fly ash quantity can be taken into account in the concrete

composition with respect to cement content and water cement ratio.

Central Pubic Works Department (CPWD) vide its circular dated May 13, 2004 has also allowed use of fly ash in all grades of concrete in pile foundations and other foundations and in M-30 and higher grades for structural concrete works. The concrete should be obtained from Ready Mixed Concrete (RMC) Plants.

10.0 Effect of quality of fly ash on concrete

The characteristics of fly ash depends upon the characteristics of coal burnt in the furnace of boiler, degree of pulverization of coal, rate and temperature of combustion, fuel/ air ratio etc. The important characteristics, which affect the performance of fly ash in concrete, are

- Loss on Ignition (LOI)
- Fineness
- Calcium (CaO) content

10.1 Loss on Ignition

When fly ash is burnt at about 1000^0 C, it suffers a loss of weight through the presence of carbonates, combined water in residual clay mineral and combustion of free carbon. The combined effect is termed the LOI. The carbon contained in fly ash has high porosity and a very large specific area and is able to absorb significant quantity of water as well as admixture. Thus increase water and admixture requirement and affect properties of concrete. It may be stated that lower the LOI, the better will be the fly ash.

10.2 Fineness

Fineness of fly ash, which is also represented in terms of specific surface area, is determined by Blaine method. This method is based on the resistance offered by material to airflow. More the surface area greater will be fineness. Fineness is also determined by wet sieve analysis and represented in terms of amount retained when wet-sieved on 45 micron (No. 325) sieve. Finer fly ash will have more reactive surface area available

to react with lime and thus more will be the pozzolanic activity of fly ash. In short, it can be concluded that finer the fly ash and lower the carbon content, the greater will be the pozzolanic activity and greater the contribution to the strength in concrete of the same workability.

10.3 Calcium (CaO) content

Fly ash consist of large amount of noncrystalline particles or glass and small amount of one or more of the four major crystalline phases; quartz, mullite, magnetite and hematite. The reactivity of fly ash is related to the noncrystalline phases or glass. Pozzolanic reactivity of fly ash is more in high calcium fly ash than low calcium fly ash. The reason for high reactivity in high calcium fly ash partially may be because of different chemical composition of glass than the glass of low calcium fly ash.

11.0 Types of Cements

The various types of the cements generally available in the market are:

- Ordinary Portland Cement - 33 Grade (as per IS: 269- 1989 - Reaffirmed 2004)
- 43 Grade Ordinary Portland Cement (as per IS: 8112 1989 - Reaffirmed 2005)
- 53 Grade Ordinary Portland Cement (as per IS: 12269 1987 - Reaffirmed 2004)
- Portland Pozzolana Cement fly ash based (as per IS: 1489 part-1- 1991- Reaffirmed 2005)
- Portland Pozzolana Cement calcined clay based (as per IS: 1489 part-2 1991 - Reaffirmed 2005)
- Portland Slag Cement (as per IS: 455 1989 - Reaffirmed 2005)

11.1 Ordinary Portland Cement (OPC 33 grade, 43 grade and 53 grade) are manufactured by intimately mixing together calcareous and argillaceous and /or other silica, alumina or iron oxide bearing materials, burning

them at clinkering temperature and grinding the resulting cement clinker with natural or chemical gypsum so as to produce cement capable of complying the IS specifications. Fly ash up to 5% conforming to IS: 3812 part 1 can be used as a performance improver in the manufacturing of these cements. The grades of these Ordinary Portland Cement are designated based on its 28-days average compressive strength requirement.

11.2 Portland Pozzolana Cement (PPC IS: 1489 part -1) fly ash based is manufactured either by intimately intergrinding Portland cement clinker and fly ash with addition of gypsum or calcium sulphate or by intimately and uniformly blending with OPC and fine fly ash. The fly ash constituent shall not be less than 15 percent and not more than 35 percent by mass of Portland Pozzolana Cement. Portland Pozzolana cement produces less heat of hydration and offer greater resistance to the attack of aggressive waters than Ordinary Portland Cement. It is particularly useful in marine and hydraulic construction and other mass construction structures. This cement is equivalent to Ordinary Portland cement on the basis of the 3, 7 and 28 days compressive strength.

11.3 Portland Pozzolana Cement (PPC IS: 1489 part -2) calcined clay based is manufactured either by intimately intergrinding Portland cement clinker and pozzolana (Calcined clay) with addition of gypsum or calcium sulphate. It can also be manufactured by intimately and uniformly blending with Portland cement and fine pozzolana. The pozzolana constituent shall not be less than 10 percent and not more than 25 percent by mass of Portland Pozzolana Cement. This type of PPC is now a days is not being manufactured by cement manufacturers because of non availability of good quality calcined clay and huge availability of good quality of fly ash in thermal power stations.

11.4 Portland Slag Cement (as per IS: 455 1989) is manufactured either by intimately intergrinding Portland cement clinker and granulated slag with addition of gypsum (Natural or Chemical) or calcium sulphate. It can also be manufactured by intimately and uniformly blending with Portland cement and finely ground granulated slag. The slag constituent shall not be less than 25 percent and not more than 65 percent by mass of Portland slag cement.

The characteristics of these cements are in the table 5.

Table 5

Type of Cement	Compressive Strength Min. (MPa)			Fineness by Blains air permeability methods, Min. (m^2/Kg)	Setting time (Minutes)	
	3 days	7 days	28 days		Initial (Not less than)	Final (Not more than)
OPC 33 grade	16	22	33	225	30	600
OPC 43 grade	23	33	43	225	30	600
OPC 53 grade	27	37	53	225	30	600
PPC (Fly ash based)	16	22	33	300	30	600
Portland Slag Cement	16	22	33	225	30	600

There are other types of special cements such as low heat cement, sulphate resistance cement and oil well cement etc., which are manufactured mostly on order basis. Details on these cements are not discussed here.

12.0 High Volume Fly Ash Concrete (HVFAC) for mass concrete and road pavements

In order to allow large volume of fly ash use in conventional concrete application, Canada Centre for Mineral & Energy Technology (CANMET) initiated research studies on structural concrete incorporating siliceous fly ash (class F) content more than 50% in the year 1985. The objective of this research was to develop a new technique for concrete, which can have adequate early strength, required workability, low temperature rise and high long-term strength.

In the HVFAC mechanism, physical and chemical factors combines at all ages to densify and bind the paste. In the early age of concrete, the important factors of strength development are (i) physical effect - fine particles of fly ash act as micro aggregates and densify the mass and (ii) chemical contribution of the formation of ettringite or related sulpho-aluminate production. In the later age hydration reaction dominate in the strength development process as additional binders are generated by reaction involving fly ash.

In HVFAC, depending upon strength requirement, generally cement content varies within the range of 100-180 Kg/m^3, water/ (cement + fly ash) range 0.30-0.40. The fly ash content is kept within 150-270 Kg/m^3. In this concrete use of superplasticizer becomes mandatory because of very low water/ (cement + fly ash) ratio. The dose of superplasticizer will depend on the requirement of workability of concrete.

View of High volume fly ash Concrete Road in NCB-Ballabgarh Campus

In India the technology transfer projects are being taken up in association with Canadian International Development Agency (CIDA), CANMET-MTL, Confederation of Indian Industry (CII) and other partner organizations. Some of the examples of projects in India made using HVFAC are as under:

- A road of approximately 2.3 km has been constructed on the campus of the Saurastra University, Rajkot, Gujarat.
- ACC Ltd. has constructed approach road at their Ready Mixed Concrete Plant in Greater Noida.
- Municipal Corporation of Delhi constructed a road pavement at Delhi.

13.0 Roller Compacted Concrete (RCC) Dams

Roller Compacted Concrete is named from the method used for construction. It is a zero slump concrete having same basic ingredients such as cement, aggregates, water, fly ash etc. but it is transported by dump trucks, spread by dozers and compacted by vibratory rollers.

The RCC technique was developed in the seventies, when the requirement of strong pavement to support massive load and movement of heavy specialized equipment arisen to Canadian logging industry for land based log sorting. Area of logging yard was about 40 acres and therefore economy of construction was also an

important factor for pavement construction. RCC met both the requirements and since than it become popular to other heavy-duty applications.

The three key factors - Economy, Performance, and High-speed construction made RCC uniquely suited method for construction of dams and also for pavements, parking areas etc. The advantages of RCC are :

1. RCC pavements do not require joints, dowels, reinforcing steel, form works or finishing and its also virtually maintenance free.

2. Allows higher substitution of cement by fly ash (up to 70%) and thus economical.

3. Reduced heat of hydration in case of mass concrete works like dam construction and thereby lesser expenses on cooling infrastructures.

4. It has the strength and durability of the conventional concrete, but the cost can compete to earth or rockfill construction.

RCC technique is very popular for dam construction and world over till 2004, more than 320 dams have been constructed / under construction using RCC method. Apart from the dam construction RCC is today used for Port, parking, storage, staging areas, military facilities, streets, intersections and low speed roads construction. For high-speed roads, it can be used for the foundation/ sub base course.

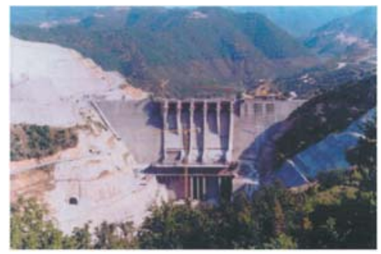
In India, RCC construction technique with about 60-68 % fly ash has been used first time in the construction of 3 dams namely saddle dam, upper dam, and lower dam of Ghatghar pumped storage scheme in Maharastra. The saddle dam is 8 m height, 284 m long and 8 m wide. The upper dam is 14.5 m height, 451 m long and 8 m wide. The lower dam is 86 m height, 450 m long. The fly ash is used upto 160 kg (68%) of the total cementitious materials of 235 Kg per cum of RCC, while the quantity of OPC used is 75 kg/m^3. About one-lac tonnes of

View of lower dam of Ghatghar pump storage scheme

fly ash from Nasik thermal power station located at about 150 km from the project site have been utilized in the construction of these dams.

Beni Haroun Dam on Elkabir river

Beni Haroun RCC dam of 118 m high & 714 m long was constructed during 1998-2000 on Elkabir river in Eastern Algeria. The mixture properties used in the per m^3 of RCC mix were ASTM type-II cement 82 kg, ASTM class F fly ash 143 kg, water 101 kg coarse aggregates 1335 kg, fine aggregates 750 kg.



Platanvryssi Dam on Nestos river

Platanvryssi RCC dam of 95 m high and 305 m long was constructed on Nestos river in Greece during 1995-97. The mixture proportions used in per m^3 of RCC mix were ASTM type-I cement 50 kg, ASTM class C type fly ash 255kg, water 133 kg, coarse aggregates 1300 kg, fine aggregate 625 kg.

14.0 Examples of use of fly ash in concrete

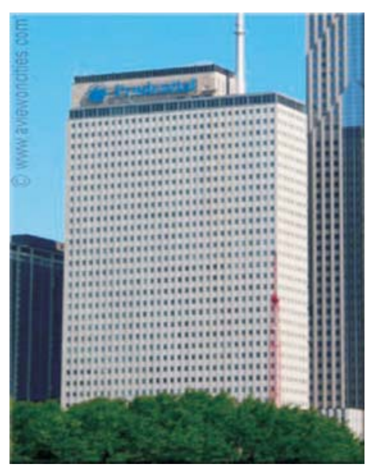
14.1 World over

World over fly ash has been successfully utilized in cement concrete and as component of Portland Pozzolana Cement/ Blended cement for more than 50 years. Some of the structures wherein fly ash has been utilized are as under:

1. Fly ash concrete was used in Prudential Building the first tallest building in Chicago after World war II.

2. About 60,000 cum of fly ash concrete with an estimated saving of 3,000 tonne of Ordinary Portland Cement was used in Lednock Dam construction in UK during the year 1955.

3. About 60,000 m^3 of fly ash concrete with 80/20 Ordinary Portland Cement/ fly ash having average slump of 175 mm was used in the piles and the foundation slab to meet the requirement of sulphate resistance concrete of Ferrybridge C power station in UK during 1964.



Prudential Building in Chicago

4. Fly ash concrete was used for all the tunnel lining and slip formed surge shafts at the Dinorwig Pumped Storage Scheme in the year 1979 & 1980 in UK mainly to provide increased resistance to attack from aggressive water.

5. In the 1980's, in Sizewell B Nuclear Power station fly ash has been used in about 3,00,000 m^3 concrete to improve workability for pumping, reduce temperature rise and increased resistance to chlorides and reduced risk of alkali aggregate reaction.

6. Fly ash in concrete was used in construction of Euro Tunnel-second largest rail tunnel in the world during 1987-94. To meet the early stripping requirement, a concrete mix containing 30% fly ash with w/c of 0.35 using high efficient water reducing admixture at a total cementitious content of 440 kg/m3 was used in the work. The strength of concrete obtained was more than 80 MPa at 28 days and permeability coefficients were 10^{-13} m/s against requirement of 70 MPa and 10^{-11} m/s.

7. Fly ash has been used in construction of world's tallest building "Petronas towers of Kuala Lampur. The concrete used in the building was of two grades 80 MPa and 60 MPa. The fly ash content was about 37.5 % of total cementitious content in mix. Construction completed in the year 1998.

Petronas Tower of Kuala Lampur

14.2 In India

In India calcined clay pozzolana as a mineral admixture was used in mass concrete work of Bhakra and Rana Pratap sagar dam works in late fifties and early sixties. A special plant was set up to produce calcined clay pozzolana in 1957 at Bhakra dam site to meet requirement of pozzolana for mass concrete work. Some of the examples of application of fly ash as a pozzolana in mass concrete works are Rihand Dam and Narora Barrage in UP, Jawahar Sagar Dam in Rajasthan and

Chandil Dam in Bihar when it has became available at thermal power stations. The use was limited because of non-availability of good quality fly ash in thermal power station.

With increasing awareness, availability of good quality fly ash in modern efficient thermal power station and concept of Ready Mixed Concrete, the use of fly ash as part replacement of cement and sand is showing increasing trends. Few examples wherein fly ash has been utilized in cement concrete are as under:

1. Fly ash from NTPC's Dadri Thermal power stations is being utilized in prestigious Delhi Metro Rail Corporation (DMRC) works at New Delhi. : More than 60,000 tonne of fly ash has been utilized in the work so far. In this project, the requirement of cement concrete was high strength, high durability (less shrinkage and & thermal crakes), low heat of hydration, easy placement, cohesiveness and good surface finish. Use of fly ash in concrete has fulfilled the entire above requirements. In this work the concrete of M-35 and above were used in structural works. The typical mix used for M-35 grade concrete is given below :

Ingredients for M-35 grade (Kg/ Cum of concrete)	**Concrete without fly ash**	**Concrete with fly ash**
Cement	364	300
Fly ash	-	120
Coarse aggregates 20 mm size	637	611
Coarse aggregates 10 mm size	421	406.6
Fine aggregates	546	442.4
Stone dust	237	300.9
Water (liter)	163.8	168
Superplasticizer (liter)	3.64	2.52

Replacing cement by fly ash has (i) reduced the peak temperature by 8^0C, (ii) the time attaining peak temperature has been extended and (iii) heat generation pattern was more uniform and gradual.

2. Fly ash concrete (M-30 grade and high performance M-60 grade) was utilized for tremie seal concrete and pile cap concrete in Bandra Worli Sea link project. Fly ash was taken from Dahanu thermal power station, Mumbai.

The mixture proportion used in this work are as under:

Ingredients	Mix Proportion (Kg/m^3)	
	Tremie seal Concrete	Pile cap Concrete
Cement (53 grade)	180	300
Fly ash	220	196
Micro silica	-	40
Water	135	136
W/cm	0.34	0.25
20 mm	550	577
10 mm	450	500
Crushed sand	465	423
Natural Sand	465	327

View of tremie seal concrete in Bandra Worli Sea link project

Admixture	2.5% HRWRA	13.4
Slump initial (mm)	Collapse	Collapse
Slump after 3 hours	180 mm	165
Compressive Strength (MPa)		
3 days	10.2	39.3
28 days	36.5	74.66
56 days	47.2	80.89

3. Self-Compacting concrete using fly ash from Kota thermal power station has been utilized for structural members of Rajasthan Atomic Power Project. Self-compacting concrete was used due to difficulties in placing concrete in structures having heavily congested reinforced bars and openings.

The details on the mix proportion used in this work are as under:

Ingredients	**Mix Proportion (Kg/m^3)**
Cement (43 grade)	250
Fly ash	200
Water	180
W/cm	0.4
20 mm	250
10 mm	374
Crushed sand	562
Natural Sand	426
Superplasticizer	3.8
Retarder	0.45
Viscosity –modifying agent	0.45
Compressive Strength (MPa) 3 days 28 days 56 days	 11.5 35 41.5

4. Recently, about 38,000 m^3 fly ash concrete has been used in main plant civil work of Rajasthan Atomic Power Project (RAPP) unit 5 &6.

View of TG deck of RAPP

5 DLF and Unitech Prefab have utilized fly ash from NTPC Dadri in concrete for residential buildings at Gurgaon Haryana.

6 Ready Mixed Concrete (RMC) plants located in Mumbai, Delhi and adjoining areas are using fly ash in concrete. These RMC plants are taking fly ash from Nasik and Dahanu thermal power stations located near Mumbai and Dadri near Delhi and supplying fly ash based concrete for various housing and infrastructure projects.

References

1 IS 3812-2003, Pulverized Fuel Ash specification, part 1 for use as pozzolana in cement, cement mortar and concrete.

2 IS 456-2000 Plain & Reinforced Concrete Code of Practice.

3 IS: 269 -1989 - Ordinary Portland Cement - 33 Grade (Reaffirmed 2004)

4 IS: 8112-1989 - 43 Grade Ordinary Portland Cement (Reaffirmed 2005)

5 IS: 12269-1987 - 53 Grade Ordinary Portland Cement (Reaffirmed 2004)

6 IS: 1489 part-1 1991 - Portland Pozzolana Cement fly ash based (Reaffirmed 2005)

7 IS: 1489 part-2 1991 - Portland Pozzolana Cement calcined clay based (Reaffirmed 2005)

8 IS: 455-1989 - Portland Slag Cement (Reaffirmed 2005)

9 ASTM International C: 618-03 Standard specification for coal Fly ash and Raw or Calcined Natural Pozzolana for use in Concrete.

10 V. M. Malhotra and AA Ramezanianpour March 1994, Fly Ash In Concrete

11 Fly ash in concrete (Properties and Performance) - Report of Technical Committee 67-FAB (RILEM)

12 Souvenir & Seminar Document, May 1996 Maharashtra India Chapter of ACI, Use of Fly ash in concrete.

13 Dr. A K Chatterjee, Concrete for the 21st Century Meeting the challenges The Indian Scenario Cement substitute Materials for concrete making The Indian Scenario.

14 MDA Thomas, KB Cripwell and PI Owens Fly Ash in concrete: An Overview of more than 30 years of Experiences in the United Kingdom.

15 N. Bhanumathidas & N. Kalidas 2002-Fly Ash for Sustainable Development.

16 V. V. Gaikwad, V. C. Shelke and R. A. Gunjal Phoenixes from fly ash-Three RCC Dams for Ghatghar Project, National Seminar cum Business Meet on use of Fly ash in Hydro Sector.

17 Mohammed Ashraf, Manish Mokal and J. Bhattacharya Fly Ash India 2005, New Delhi Use of Fly ash in high Performance Concrete & Self Compacting Concrete.

18 US department of Transportation, Federal Highway Administration -Fly ash Facts for Highway Engineers - Technology Transfer

19 Standard Practice for selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)